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Measurement of Ion Flow Velocity Field Associated with Plasma Hole Using Laser Induced Fluorescence Spectroscopy

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"Plasma hole" is a singular vortex spontaneously formed in an electron cyclotron resonance plasma. So far the ion flow velocity field associated with the plasma hole has been measured with a directional Langmuir probe (DLP). Here we present the first result of measuring azimuthal and radial flow velocity profiles of the plasma hole in an argon plasma using a laser induced fluorescence (LIF) Doppler spectroscopy, which demonstrates the effectiveness of LIF spectroscopy for absolute flow velocity measurement of the plasma hole. The azimuthal flow was found to be nearsonic rotation, the Mach number of which was approximately 0.65, which agreed with the previous DLP measurements. The radial flow was found to be outward and the velocity was considerably small, which is different from the previous DLP measurements of the plasma hole in a helium plasma. The possible causes of this discrepancy are discussed.

Keywords: flow measurement, laser induced fluorescence, LIF, vortex, plasma hole, HYPER-I device

1. Introduction

The importance of plasma flow structures has been widely recognized in various fields of plasma research such as fusion plasmas, space and astrophysical plasmas and laboratory plasmas, and many studies on plasma flow related phenomena have been performed extensively. In particular, vortex has been a topic of interest in plasma physics due to its deep connection to turbulence and transport phenomena.

Recently we have observed a singular vortex, which is spontaneously formed in a laboratory electron cyclotron resonance (ECR) plasma. This vortex is referred to as "plasma hole" [1-3], since one of the remarkable characteristics of this vortex is a density hole formed around the central axis. The ion flow velocity field of the plasma hole has been observed as a monopole vortex with inward radial flow, and the maximum azimuthal rotation velocity has been found to be near sonic or up to supersonic in some cases. In our previous studies, the ion flow velocity measurements have been performed with a directional Langmuir probe (DLP) [4]. Although the DLP provides an easy-to-use way to measure ion flow velocity profiles, there is still an ambiguity in determining the absolute velocity, the value of which depends on the choice of a model for analysis. In order to clarify the formation mechanism of the plasma hole, a precise ion flow velocity field is needed. For that purpose we have developed a laser induced fluorescence (LIF) [5] Doppler spectroscopy system [6], which is capable of determining time-averaged absolute flow velocity of ions and meets our objective. Since a suitable LIF scheme for argon ions at visible wavelength is available [7-9], we employed it to determine the ion flow velocity field of the plasma hole in an argon plasma (Ar plasma hole).

In this paper, the first result of absolute ion flow velocity measurement of the Ar plasma hole using LIF Doppler spectroscopy is presented. In Sec. 2, the experimental setup and the LIF scheme used in this study are described. The experimental results including the ion flow velocity profiles obtained by LIF measurements are shown and discussed in Sec. 3. Concluding remarks and future tasks are given in Sec. 4.

2. Experimental Setup

The experiments were performed in the High Density Plasma Experiment (HYPER-I) device at the National Institute for Fusion Science (Fig. 1). HYPER-I is a

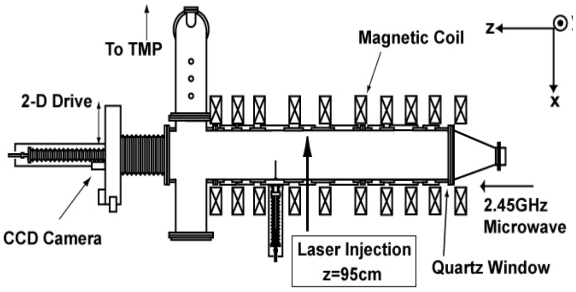

Fig. 1 Schematic of the HYPER-I device.

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cylindrical plasma device (30 cm in diameter and 200 cm in length) with ten magnetic coils. Plasmas are produced by ECR heating with a microwave of frequency 2.45 GHz. In the present experiments, the microwave input power was approximately 2.5 kW and the pressure of an argon gas was 8.3×10^{-5} Torr. The magnetic field configuration was a so-called magnetic beach (923 G at z = 10 cm, 875 G at z = 60 cm (ECR point), where z represents the axial position measured from the microwave injection window).

Schematic diagram of the experimental setup is shown in Fig. 2. A tunable dye laser (Sirah Cobra-Stretch) is pumped by an Nd:YAG laser (Spectra-Physics Quanta-Ray PRO) pulsed at 30 Hz. The dye laser energy is approximately 60 mJ/pulse. The laser beam is transferred with mirror optics and injected to the plasma from a side viewing port at z = 95 cm. A beam dump is installed to suppress the scattered light. The laser wavelength is controlled with a PC and measured with a wavemeter (Coherent WaveMate Deluxe). The laser wavelength is tuned to 611.49 nm, which excites the $3d\ ^2G_{9/2}$ metastable state of argon ions to the $4p\ ^2F_{7/2}$ state. The latter has a very short lifetime and can decay spontaneously to the $4s\ ^2D_{5/2}$ state by emitting a photon at 460.96 nm which constitutes the fluorescence signal.

The LIF technique for velocity measurement takes advantage of the Doppler effect. The Doppler shift condition for the present experiment is given by

$$2\pi\Delta\nu = \mathbf{v}\cdot\mathbf{k} = -\upsilon_x k_{\mathrm{laser}} \qquad (1)$$

, where $\Delta\nu$ is the difference between the laser frequency and the transition frequency of a stationary metastable ion, $\mathbf{v}$ the ion velocity, and $\mathbf{k}$ the incident laser photon wave vector. Note that when an ion moves to the direction $x>0$, the scalar product in eq. (1) becomes negative in the coordinate system used in this study. Since the Doppler shifted LIF spectra in the present experiments were taken as a function of wavelength, we rewrite eq. (1) as follows:

$$\Delta\lambda = (\lambda_{\mathrm{laser}} - \lambda_{\mathrm{trans}}) = \lambda_{\mathrm{trans}}\frac{\upsilon_x}{c} \qquad (2)$$

, where λ_{laser} is the laser wavelength, λ_{trans} the $3d\ ^2G_{9/2} - 4p\ ^2F_{7/2}$ transition wavelength, υ_x the x-component of ion velocity parallel to the laser beam path, and c the speed of light. Since only those ions with the velocity satisfying the Doppler shift condition are excited by the laser photons, an LIF spectrum is obtained by scanning the laser wavelength around the $3d\ ^2G_{9/2} - 4p\ ^2F_{7/2}$ transition wavelength and recording the fluorescence intensity. The collection optics for LIF emission consists of a lens, a filter (the center wavelength is 461.19 nm and the transmission bandwidth is 1.16 nm) and a photomultiplier tube (PMT) (Hamamatsu R3896). It was positioned to view the plasma at an angle of 90 degree from the laser beam and mounted on a two dimensionally movable bench, so that the focal point can be adjusted in the rectangular region of $-6\ \mathrm{cm} < x < 6\ \mathrm{cm}$ and $-6\ \mathrm{cm} < y < 6\ \mathrm{cm}$. Also the height of the laser beam path can be varied by changing the position of the mirror in the range of $-6\ \mathrm{cm} < y < 6\ \mathrm{cm}$. Both movements enable us to conduct local LIF measurements. Azimuthal (rotational) component of the ion flow can be measured by changing the vertical position of the collection optics in accordance with the height of the laser beam, while the horizontal position of the collection optics is fixed at $x=0$. On the other hand, radial component can be measured by changing the horizontal position of the collection optics, while the height of the laser beam is fixed at $y=0$. Assuming an axial symmetry condition, we can determine the flow velocity field. The LIF signal (output of PMT) is amplified by a high speed amplifier (Hamamatsu C5594) and is averaged over 100 samples with a gated integrator (Stanford Research Systems SR250) synchronized with the laser pulse, where the Active Baseline Subtraction mode is used to cancel the baseline drift. The position and width of the gate for SR250 is adjusted by monitoring the LIF signal on a digital oscilloscope.

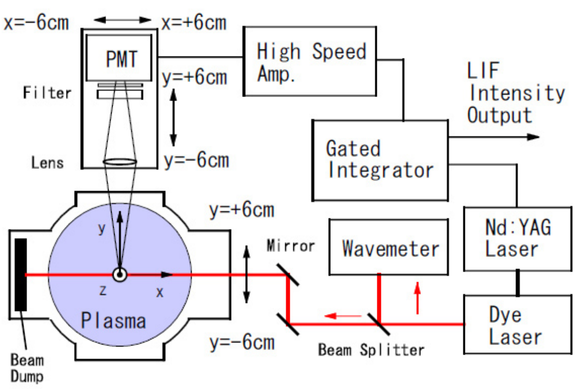

Fig. 2 Schematic of the experimental setup.

3. Results and Discussions

Spontaneous formation of the Ar plasma hole was observed under the experimental conditions mentioned in Sec. 2. Typical electron density and electron temperature were $1-5\times10^{10}\ \mathrm{cm}^{-3}$ and 10 eV, respectively. A visible light image taken by a CCD camera is shown in Fig. 3.

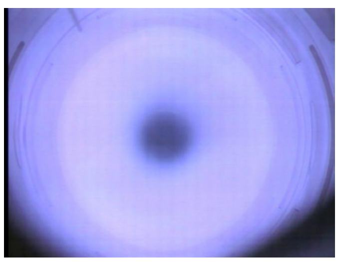

Fig. 3 A CCD image of the Ar plasma hole, where the dark core (hole) is formed in the central region. The diameter of the hole is approximately 70-80 mm.

This hole structure remained stationary during the whole discharge duration time (240 s), therefore it was possible to obtain one LIF spectrum by one shot of the plasma discharge. In addition, the plasma hole showed excellent reproducibility, which enables us to compare the LIF spectra obtained in different shots.

Examples of the LIF spectra are shown in Fig. 4 as a function of laser wavelength, where the Voigt function is used as the fitting curve for taking the effect of nonnegligible laser linewidth into account. Doppler shifts from the transition wavelength for stationary metastable ions at y = 0 are clearly seen in the spectra taken at $y = \pm 6$ cm. The maximum Doppler shift of 0.0068 nm was observed at $y = +6$ cm, which corresponds to a velocity of 3.2 km/s. It should be pointed out that the widths of those spectra do not give the ion temperatures directly, since the linewidth of our dye laser is wider than the Doppler broadening widths of the ion velocity distribution functions. A laser that has narrower bandwidth is needed to obtain the ion velocity distribution function directly. A tunable external cavity diode laser is a good candidate and is now being prepared for our future work.

Figure 5 (a) shows the azimuthal flow velocity profile determined from the Doppler shifts of the LIF spectra. Error bars mainly come from the stability and precision of the laser wavelength, which exhibits slight temporal change during the experiments. In order to determine the laser wavelength more precisely, a wavelength reference such as absorption lines of Iodine should be measured simultaneously. Figure 5 (a) indicates that the azimuthal rotation is in clockwise direction, which corresponds to that of the $\mathbf{E} \times \mathbf{B}$ drift driven by an outward electric field. In the hole region (-3 cm $< y <$ 3 cm), rigid-like rotation is clearly seen, which is the property of azimuthal flow of the plasma hole. This result agrees with our previous DLP measurements in a similar Ar plasma hole with a minor correction for the calibration factor. Ion sound speed in the Ar plasma hole, where the electron temperature is 10 eV, is 4.9 km/s, thus the maximum Mach number obtained in the present experiments at $y = +6$ cm was approximately 0.65. We can conclude that the azimuthal flow velocity of the Ar plasma hole attains near sonic range, which is a characteristic of the plasma hole in which the charge neutrality breaking occurs spontaneously and a strong radial electric field exists as a consequence [10, 11]. Although the azimuthal velocity attains nearsonic value, we have not so far observed any apparent effect of compressibility in azimuthal direction. Slight asymmetry in the azimuthal velocity profile is found in the region of $y < -4$ cm. Since the grounded stainless steel shaft of an axially inserted probe was located at $x = -6.3$ cm and $y = -4.8$ cm, the electric field in the vicinity of the

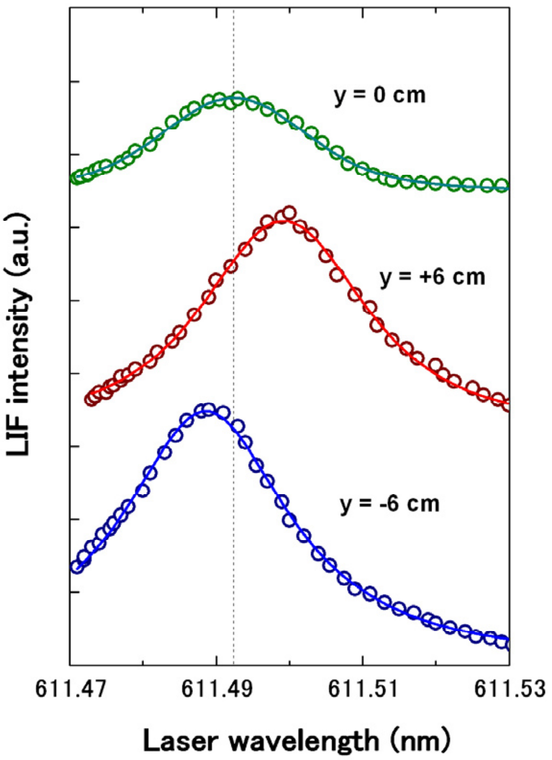

Fig. 4 LIF spectra taken at three different positions y=0, +6, -6 cm with Voigt function fitting curves. Doppler shifts from the wavelength for stationary metastable ions at y=0 cm are evident at y=±6 cm.

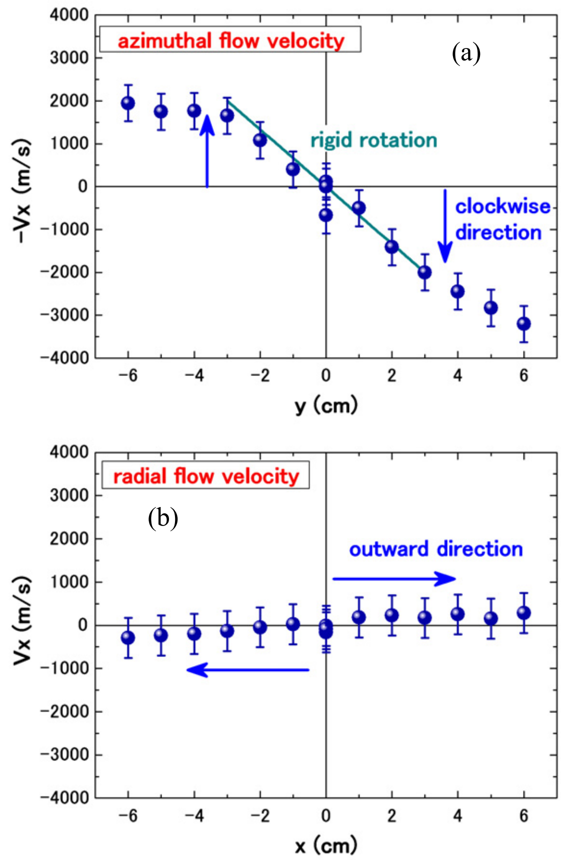

Fig. 5 Ion flow velocity profiles determined by the LIF Doppler Spectroscopy. (a) The azimuthal flow velocity. (b) The radial flow velocity profile.

probe shaft might be disturbed. As a consequence, the $\mathbf{E}\times\mathbf{B}$ velocity profile was also disturbed, which may result in a slightly asymmetric flow profile.

Figure 5 (b) shows the radial flow velocity profile of the Ar plasma hole. In contrast to the azimuthal flow velocity, the absolute values of the velocities are considerably small. The direction of radial flow was outward in this case. This is different from the previous observation of radially inward flow of the plasma hole in a helium plasma (He plasma hole), however, we should not draw a hasty conclusion that this result denies the DLP measurements. It should be pointed out that the direction of radial flow is not determined by the magnitude of viscosity only, the relation between azimuthal rotation frequency and ion cyclotron frequency, detailed vorticity profile, and collisional effect should be taken into account. Moreover, the previous DLP measurements were performed in a different ion-species plasma at different axial positions; this discrepancy might be attributable by considering the difference of ion mass and three-dimensional flow pattern of the plasma hole. In the present experiments the DLP measurements were not possible due to the existence of high energy electrons in the hole region, which significantly affected the ion saturation current and disabled a straightforward application of the DLP formula [12]. The radial density gradient may also affect the DLP measurements. Careful considerations for the analysis of DLP results are needed. Even under the influence of high-energy electrons and density gradient, the LIF spectroscopy can work as a powerful tool for measuring absolute ion flow velocity. Therefore we can conclude the effectiveness of LIF spectroscopy was confirmed by the present experiments.

4. Conclusions

We have developed an LIF spectroscopy system, which is capable of determining absolute flow velocity of metastable argon ions, and applied it to measure the ion flow velocity field associated with the Ar plasma hole. Azimuthal flow velocity profile measurements showed high-speed azimuthal rotation, the maximum value of which was 3.2 km/s, which corresponds to the Mach number of approximately 0.65. Observed near sonic rotation agrees with the previous DLP measurements. In contrast, radial flow velocity profile measurements gave outward-directed small velocities. This result implies the possibility of axial position dependence of the flow pattern of the plasma hole.

The plasma hole was first observed in a helium plasma and investigated extensively. Therefore the LIF spectroscopy for the He plasma hole is worth conducting. However, there is no suitable LIF scheme for helium ions at visible wavelengths, we are planning to apply the LIF spectroscopy system described in this paper to the helium plasma with a small amount of argon impurity gas. Preliminary experiments were performed and showed promising results that the introduction of argon gas was not destroy the He plasma hole structure and the LIF signals of impurity argons were possible to measure under such conditions.

Acknowledgments

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[1] K. Nagaoka, A. Okamoto, S. Yoshimura, M. Kono and M. Y Tanaka, Phys. Rev. Lett. **89**, 075001 (2002).
[2] S. Yoshimura, A. Okamoto and M.Y. Tanaka, J. Plasma Fusion Res. SERIES **6**, 610 (2004).
[3] M. Y. Tanaka, K. Nagaoka, A. Okamoto, S. Yoshimura and M. Kono, IEEE Trans. Plasma Sci. **33**, 454 (2005).
[4] K. Nagaoka, A. Okamoto, S. Yoshimura and M. Y. Tanaka, J. Phys. Soc. Jpn. **70**, 131 (2001).
[5] R. A. Stern and J. A. Johnson III, Phys. Rev. Lett. **34**, 1548 (1975).
[6] A. Okamoto, S. Yoshimura, S. Kado and M. Y. Tanaka, J. Plasma Fusion Res. **80**, 1003 (2004).
[7] N. Sadeghi, T. Nakano, D. J. Trevor and R. A. Gottscho, J. Appl. Phys. **70**, 2552 (1991).
[8] M. J. Goeckner, J. Goree and T. E. Sheridan, Phys. Fluids B **3**, 2913 (1991).
[9] D. A. Edrich, R. McWilliams and N. S. Wolf, Rev. Sci. Instrum. **67**, 2812 (1996).
[10] S. Yoshimura, A. Okamoto and M. Y. Tanaka, Bull. Am. Phys. Soc **48**, 68 (2003).
[11] M. Y. Tanaka, K. Nagaoka, A. Okamoto, S. Yoshimura and M. Kono, Phys. Scripta **T107**, 40 (2004).
[12] T. Shikama, S. Kado, S. Kajita and S. Tanaka, Jpn. J. Appl. Phys. **43**, 809 (2004).